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The Influence of Static and Dynamic Platform Characteristics on Hole Quality, Cycle Time and Tool Wear When Drilling Aerospace Metal Alloy Stacks

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The Influence of Static and Dynamic Platform Characteristics on Hole Quality, Cycle Time and Tool Wear When Drilling Aerospace Metal Alloy Stacks

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Abstract

The need to drill several thousand holes per aircraft through composite and hybrid material stacks is a large challenge for the aerospace assembly process. The ability to produce high quality holes for the lowest tooling costs is at the forefront of requirements for aircraft assembly factories worldwide. Consequently, much research has been conducted into tool design and development, however, the effect of drilling platform characteristics has not been well covered in literature.

Respectively, this research has compared the drilling abilities of a 5-axis precision CNC platform, a hybrid parallel kinematic machine and an articulated robotic arm fitted with a drilling module. In-process force measurement and post process hole and tool analysis methods were used to better understand the effect of static and dynamic platform characteristics on the achievable hole quality, cycle time and tool wear when drilling aerospace metal alloy stacks.

Consequently, tool supplier recommended drilling parameters were found to perform well on the precision CNC platform but were less than optimum for the hybrid parallel kinematic machine and articulated robotic arm fitted with a drilling module. As a result, commercially viable optimised drilling parameters were generated for each platform, leading to improved hole quality, reduced cycle time and a maintained rate of tool wear. This paper has initiated the development of commercially relevant research questions however, further research with more challenging conditions, materials and machining programmes are required as further research.

Introduction

The need to drill several thousand holes per aircraft [1] through metal, composite and hybrid material stacks is a large challenge for the aircraft assembly industry. The ever increasing need for lower machining costs, quicker manufacturing times and highly repeatable manufacturing processes has resulted in a dramatic increase of the scrutiny placed on machine-tool combinations in aircraft assembly factories.

With respect to cutting tools individually, much literature has focused on the effect of cutting tool geometry, tool material and tool specific process parameters [2], [3]. Resultantly, the use of specialist and process-specific cutting tools is common practice during the aircraft manufacturing processes.

Conversely, with respect to investigations relating to machining platforms, the effect of drilling platform characteristics has not been as thoroughly covered in literature. Machining principles indicate that the stiffness (specifically dynamic stiffness [4]) of a machining platform is one of the most important characteristics required to generate high quality holes. Likewise, platform accuracy, mobility and working envelope volume are important characteristics which can effect a platform's ability to operate at a high rate and low cost, as required by modern aircraft assembly factories.

Therefore, the aim of this research was to advance the understanding of the effects of static and dynamic platform characteristics on hole quality, tool condition and cycle time when drilling stacked aerospace materials. This is the focus of on-going research at the Northern Ireland Technology Centre (NITC).

Drilling Platforms

The platforms for this research were chosen based on the breadth of their characteristics. Firstly, a small 5-axis computer numerically controlled (CNC) machine was to be the bench mark of all experiments (Figure 1). This is because this platform is similar in design to the platforms used within tooling companies to evaluate the performance of their cutting tools during design and testing. It was a Cartesian co-ordinate machine in which X, Y and Z axes were controlled by the machine head while axes A and B were controlled by the table. It compromised of a through tool liquid coolant system and external flood lubrication. The design of this platform is common throughout precision machining machines and is thought of as a rigid and accurate machining platform.

Figure 1. Platform 1, DMU 50 eVo CNC machining platform

The second platform under investigation was the Güdel Exechon XQ701 platform. It was a hybrid parallel kinematic machine (HPKM) consisting of three struts connected to two rotary axes, enabling positioning of the spindle. This platform has been designed to be moved using an automatic guided vehicle (AGV) within an aerospace factory, and has additional work envelope in the Z-axis due to a moving vertical gantry. It was supplied with a through tool minimum quantity lubrication (MQL) coolant system and retro-fitted with an external mist coolant system blowing across the drill tool towards an extraction system. This platform has previously been used in extensive tool wear tests by the NITC and has proved to be a rigid, consistent platform for drill testing [5]. The part was fixed to a rigid machining table mounted at waist height within the working envelope of the machine (Figure 2).

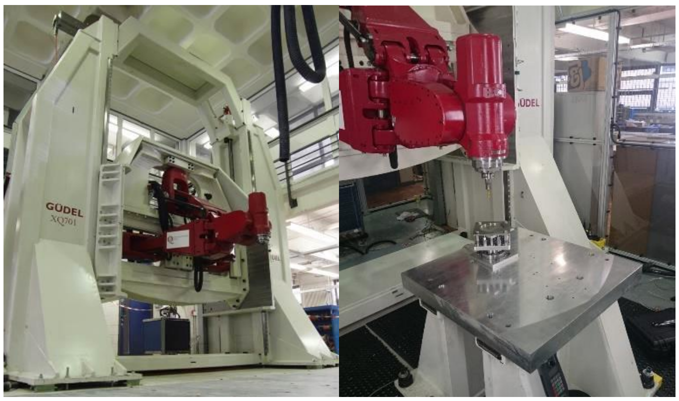

Figure 2. Güdel Exechon XQ701 HPKM platform and machining table

The final platform researched was a six degree of freedom (6 D.O.F) articulated robot arm from KUKA Robotics, fitted with an ALEMA drilling module. The drilling module was a self-contained unit enabling clamping, self-normalisation, drilling and extraction, fastener insertion and fixing. This platform could be either fixed to factory floor or plinth (as in this case) or operated from a moving gantry to increase the working envelope. It was supplied with a through tool MQL system and an external mist coolant system identical to that of the Exechon. Again, the part was fixed at waist height to a rigid machining table similar design and robustness to that of the Exechon (Figure 3).

Figure 3. KUKA arm with ALEMA drilling module without plinth

Methodology Overview

The following methodology and each of the following subsections were used when studying the characteristics of each platform and developing unique, optimised machining parameters:

1. Drilling forces and torque were recorded in process using a Kistler 9272 4 component dynamometer, 5070A Charge Amplifier and 5697 Data Acquisition Unit.
2. Tool microscopy was conducted using a modified Nikon SMZ800N optical microscope at equal one stack intervals.
3. Manufacturer's recommended speeds and feeds (MRSAF) were used to drill and countersink a minimum of 8 stacks (7.5m in length) in accordance with Step 1 and 2.
4. Static and dynamic stiffness of each platform was evaluated through the use of a HBM MX440 signal amplifier with a 10kN force sensor and MAL Inc's CUTPro Modal Analysis software, respectively.
5. In accordance with the results obtained from Steps 1 – 4 and engineering experience, process parameters were optimised to minimize tool chatter, drilling forces and torques, cycle time and tool wear.
6. Drilled stacks were de-burred, de-greased and cleaned before a selection were measured using a DEA Global Status coordinate measurement machining (CMM), equipped with a 20 x 3mm Renishaw Touch Probe and PC-DMIS software.
7. Finally, the surface roughness of five holes from each stack were measured using a Taylor Hobson Surtronic S-100 Series Surface Roughness Gauge.

Test Coupons and Fixturing

Measurement of each aluminium alloy 7475 T7351 coupon showed an average thickness of 6.35 mm and X-Y dimensions of 171mm x 172mm. Each stack consisted of two coupons placed one above of the other, giving a total drilling depth of 12.7mm. In order to make the best use of the available aluminium alloy coupons, a circular hole pattern containing 74 holes was designed (Figure 4). This resulted in a drilling distance of 940mm per stack.

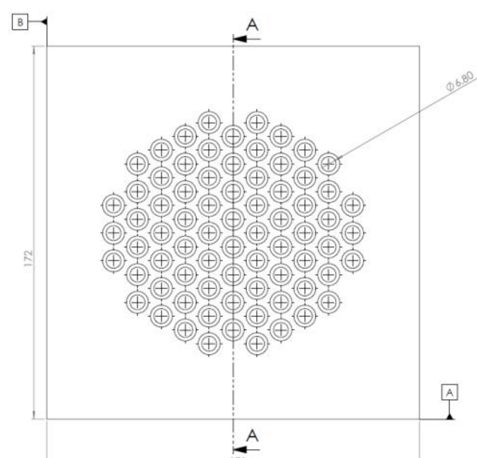

Figure 4. Drilling pattern, datum edges and coupon measurements

For all coupons machined on all platforms, a picture frame fixture system was developed which provided peripheral clamping force to the stack (Figure 5). Coupon datum surfaces identified in Figure 4 were located against 3 dowel pins which provided accurate positioning for repeated coupon placement. Likewise, the same datum surfaces of the stacks were used for measurement and analysis procedures as documented further in this paper.

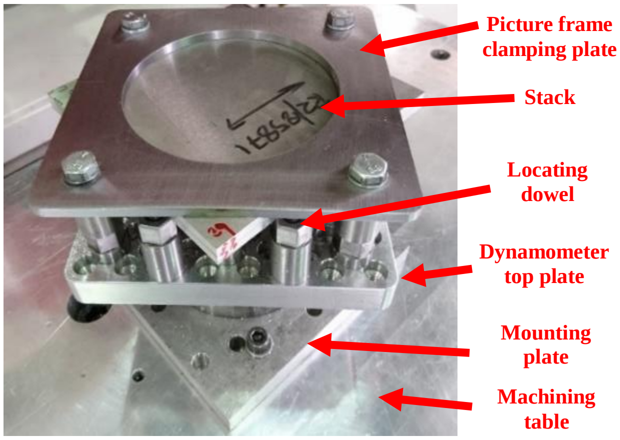

Figure 5. Picture frame fixture, force dynamometer (hidden) and mounting plate

Cutting Tool

Specifications of the tool used through the research is shown in Table 1. The tooling supplied by SECO Tools was a commercially available coated carbide drill with countersink, ideal for metal exit. Drilling with countersink is common practice in the aerospace industry and hence for the purposes of this research, in parallel with the realistic expectation that a platform needs to be commercially capable, drilling with countersink was a favourable choice for this investigation.

Table 1. Tool specifications

Tool ID	SD203A-C45-6.8-21-10R1
Cutter Material	TiN coated carbide
Drill Tip Geometry	140°
Countersink Geometry	90°, 2 Flute
Suitable for Exiting	Metallics
Through Tool Coolant	Yes

MRSAF Parameters

The MRSAF parameters are illustrated in Table 2. As described previously these are the base line parameters provided by the tooling manufacturer when drilling aluminium alloy 7475 T7351.

Table 2. Machining parameters under MRSAF conditions

Drilling	Surface Speed (m/min)	225
	Feed Per Rev. (mm/rev)	0.2
	Spindle Speed (rpm)	10532
	Feed rate (mm/min)	2106
Exit	Surface Speed (m/min)	As above
	Feed Per Revolution	
	Spindle Speed (rpm)	
	Feed rate (mm/min)	
C.sink	Surface Speed (m/min)	As above
	Feed Per Revolution	
	Spindle Speed (rpm)	
	Feed rate (mm/min)	

Modal Analysis Optimisation

Modal analysis – sometimes referred to as 'tap testing' – was carried out to determine the flexibility in the tool/holder/spindle/platform stack kinematic chain. An accelerometer was attached to the side of the tool tip and an impact hammer (also containing an accelerometer) was used to strike the tool tip directly opposite the tool accelerometer. The software captured the impact force and the output vibration at the tool tip, which it then used to create a frequency response function and determine the natural frequencies in the platform. Typically, lightweight structures (the tool, holder, etc.) vibrate at high frequencies, whilst the heavier structures (frames, columns, etc.) vibrate at low frequencies. By understanding the natural frequencies in the system, the software predicted spindle speeds which avoided chatter frequencies.

During unstable machining or drilling, regenerative vibrations would occur which could cause the tool to oscillate across, or precess around, its major axis. Resultantly, this deviation from the major axis could be seen as increased drilling forces in the X and Y directions (with some increase in Z force due to unequal tool loading). Therefore, in terms of validating the modal analysis optimisation process, not only could hole quality be measured through the CMM but by achieving low X and Y drilling forces, the tool would indicate that it was drilling without vibration.

Results and Discussion

Static Stiffness

All three platforms were tested in the condition that they would be in when drilling. This meant the DMU and Exechon continually read and operated drive motors further along the kinematic chain to maintain spindle position and orientation. The ALEMA however, in normal operation began to drill when the pressure foot had reached a predetermined force, brakes had been engaged on all axis of the articulated robot arm and the drive motors had been disengaged. No motors exterior of the drilling module were in operation while drilling, countersinking or tool retraction occurred.

The results shown in Figure 6, clarify initial perceptions with regard to the variations in platform design. That is that the DMU is the stiffest, closely followed by the Exechon, while the ALEMA is the least stiff of the three platforms. Similarly, it is common to see that all platforms deflect at a linear rate as the force increases, recovering to a near zero deflection value when the force is removed. This in turn clarifies that the design of each platform is capable of operating under Z-axis forces up to this magnitude, without severe misalignment or damage to the drive motors.

Hole Diameter – MRSAF and Optimised Parameters

The ability for a machine-tool combination to produce a hole which passes quality inspection is a fundamental need of any drilling process. Hence, a h11 (+90µm) hole tolerance was placed on all holes subjected to measurement via CMM. Due to the use of dowel pins which ensures correct alignment of upper and lower coupons, only 64 of the 74 holes drilled in each coupon could be measured without the probe colliding with the dowel. In alignment with the Methodology Overview described previously, the resultant optimised parameters for each platform are illustrated in Table 3.

Table 3. Final optimised parameters for all platforms

		DMU	Exechon	ALEMA
Drilling	Surface Speed (m/min)	311.9	306.6	313.7
	Feed Per Rev. (mm/rev)	0.2	0.2	0.2
	Spindle Speed (rpm)	14600	14350	14685
	Feed rate (mm/min)	2921	2870	2930
Exit	Surface Speed (m/min)	As above	As above	As above
	Feed Per Revolution			
	Spindle Speed (rpm)			
	Feed rate (mm/min)			
C.sink	Surface Speed (m/min)	As above	As above	As above
	Feed Per Revolution			
	Spindle Speed (rpm)			
	Feed rate (mm/min)			

As expected from the stiffest machine, the DMU platform produced repeatable, almost identically sized holes when drilling under MRSAF (Figure 7). Furthermore, following the optimisation process, the process capability (Cp) rose from 5.91 to 6.44, while the process capability index (Cpk) value only increased slightly, from 2.26 under MRSAF to 2.43. This proved the benefit of the optimisation process, even on a precision CNC platform. Changing from MRSAF to optimised parameters improved the cycle time by 13.6%, decreasing from 1.62sec/hole to 1.40sec/hole.

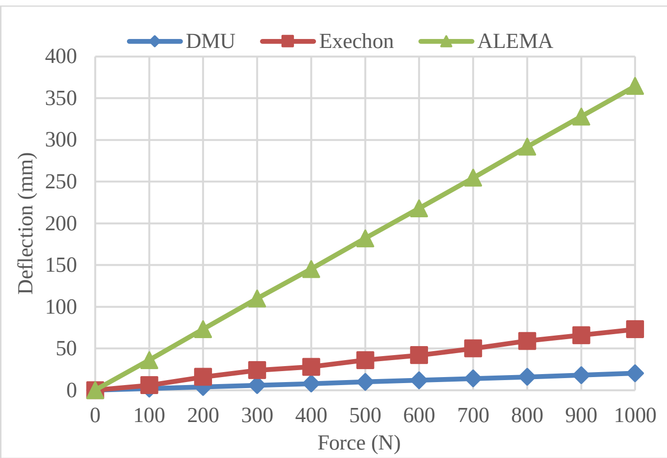

Figure 6. Static stiffness of each machining platform

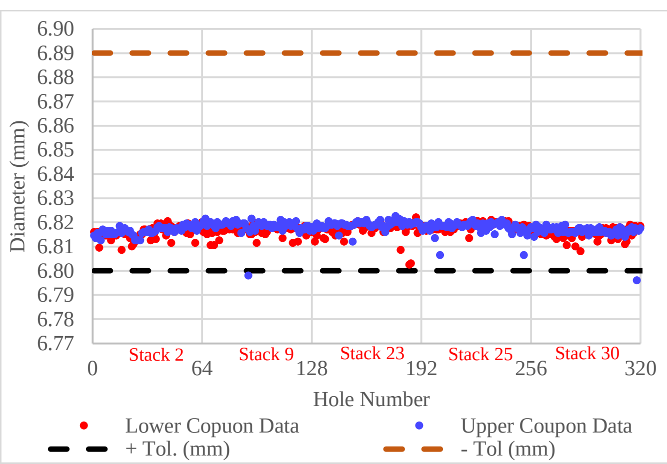

Figure 7. Upper and lower coupon hole diameters of all 64 holes drilled in stacks 2, 9, 23 (MRSAF), 25 and 30 (optimised) for the DMU platform

Comparatively, the Exechon platform produced hole diameters as displayed in Figure 8. Both MRSAF and optimised parameters are well within predetermined tolerance, however, the benefit of the optimisation process is more clearly defined than with the DMU. Cp values almost quadrupled from 1.73 to 6.44, matching that of the DMU. However, the Cpk values also followed suit, increasing from 1.02 to 3.95 (Figure 9). Simultaneously, the cycle time for final optimised parameters was 2.26sec/hole compared to 2.03sec/hole for MRSAF. This was due to the insertion of a 0.5sec dwell between each hole, a necessary requirement to facilitate the cooling of the tool by the external mist coolant.

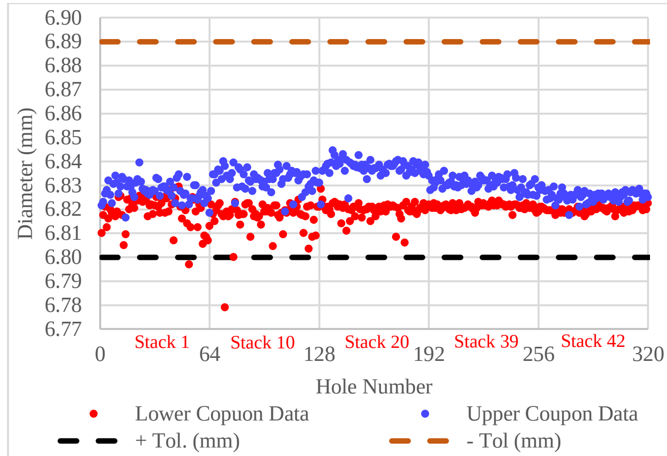

Figure 8. Upper and lower coupon hole diameters of all 64 holes drilled in stacks 1, 10, 20 (MRSAF), 39 (1st optimisation) and 42 (Final optimisation) for the Exechon platform

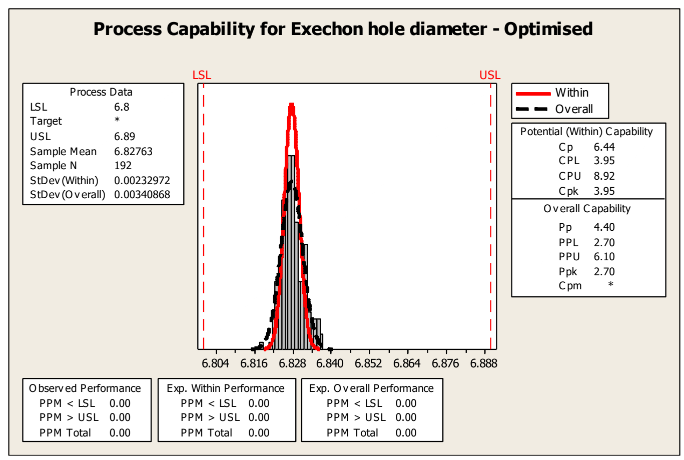

Figure 9. Process capability for Exechon drilling platform following optimisation

As with the Exechon, the hole diameters shown in Figure 10 clearly display the benefit of the optimisation process for the ALEMA drilling platform. Cp and Cpk for MRSAF were calculated as 1.14 and 2.00 respectively, indicating low process variation but low capability due to the number of undersized holes. Post optimisation, Cp rose to 3.05 demonstrating the ability of the optimisation process to increase the process capability. Unlike the other two platforms, the Cpk dropped to 0.82 as the process mean shifts closer towards the nominal hole diameter of 6.8mm. Due to the increased feed rate, the cycle time was reduced from 12.8sec/hole to 12.5sec/hole after optimisation, an improvement of 2.3%. This cycle time is much larger than that of the other two platforms due to the time required for the pressure foot of the ALEMA to 'clamp-up' before drilling could commence.

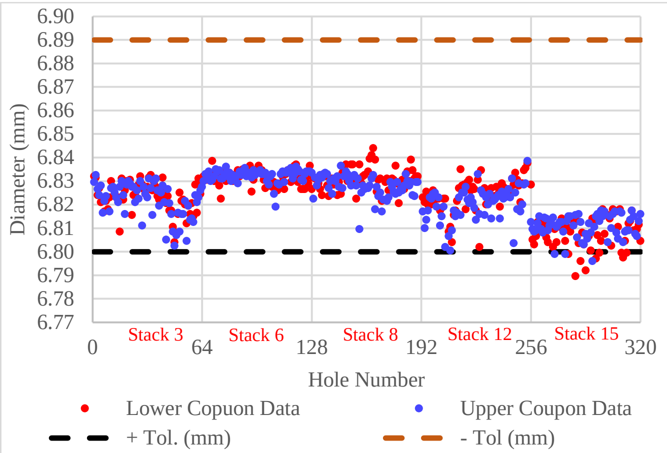

Figure 10. Upper and lower coupon hole diameters of all 64 holes drilled in stacks 3, 6, 8 (MRSAF), 12 (1st optimisation) and 15 (Final optimisation) for the ALEMA platform

Drilling Forces and Torque

Drilling forces in the X, Y and Z directions are presented as Fx, Fy and Fz respectively while the torque about the vertical (Z) axis is represented by Mz. The typical drilling forces and torques recorded by the dynamometer for a single countersunk hole are shown in Figure 11. Initial contact of the tool with the workpiece, constant drilling, tool breakthrough and countersinking can clearly be identified.

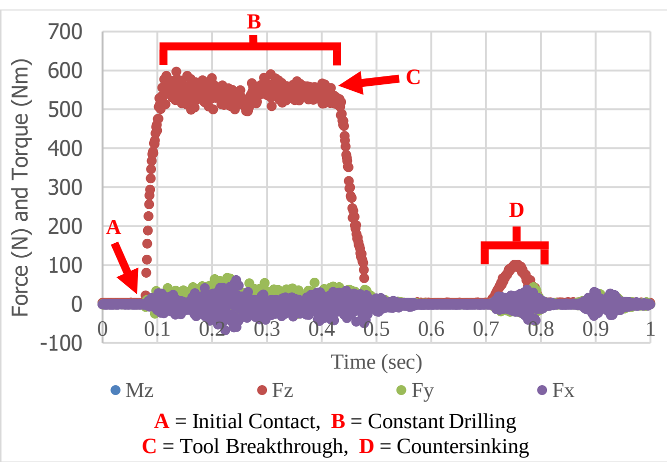

Figure 11. Typical force and torque pattern for a countersunk hole

However, due to the application of the pressure foot before drilling, the force and torque pattern for the ALEMA is as illustrated in Figure 12. For the purposes of this research, after several test holes, a pressure foot force of 800N was found to be the minimum force required to prevent chatter when countersinking. However, the vertical force (Fz) is not the superposition of the drilling forces and the pressure foot as expected, but rather the force remained close to the pressure foot value. This was due to the flexibility of the robotic arm as displayed in Figure 6. Likewise, the pressure foot masked the true magnitude of the Fx, Fy and Mz forces and torque, rendering optimisation through minimisation of the forces and torques an impossible task.

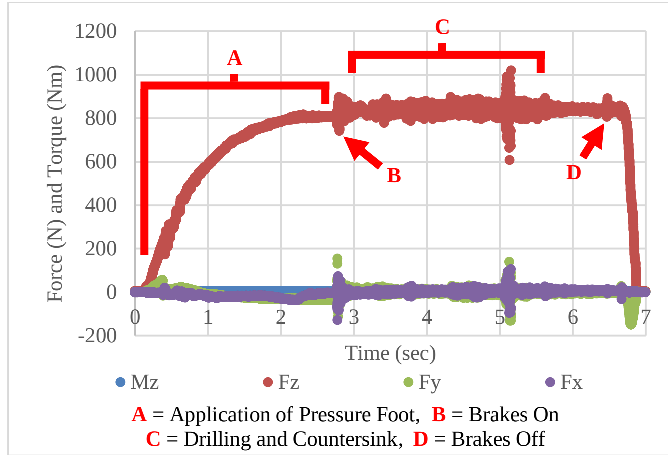

Figure 12. Typical force and torque pattern for a countersunk hole with application of a pressure foot

As displayed in Figure 13, the optimisation process for the Exechon (and likewise the DMU) was successful in lowering the drilling forces and torques.

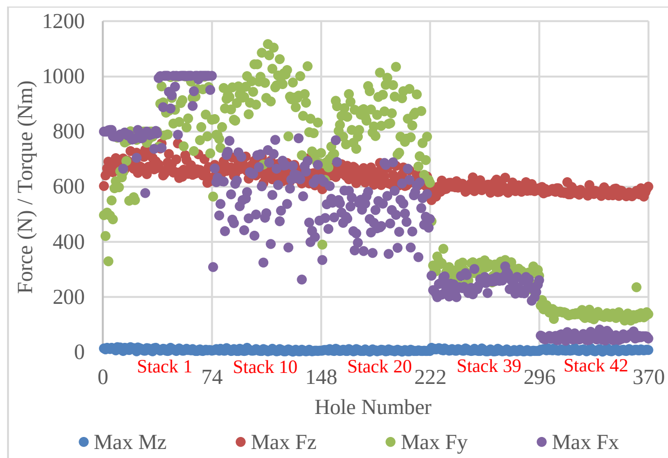

Figure 13. Forces and torque for 'Constant Drilling' phase (Figure 11) of stacks 1, 10, 20 (MRSAF), 39 (1st optimisation) and 42 (Final optimisation) for the Exechon platform

Throughout all drilling trails, the DMU and Exechon executed each machining routine without interruption. The ALEMA, however, was unable to drill several holes under MRSAF and optimised parameters due to a drilling module 'torque limit' being met. This was due to the coolant not being adequately applied to the cutting zone, because the pressure foot obstructed direct line of sight to the tool. The supply of coolant by the inbuilt through tool MQL system was ineffective for the material used in this project.

Surface Roughness

The same stacks from each platform measured with the CMM to generate the hole diameter data of Figure 7, Figure 8 and Figure 10 were subjected to surface roughness measurements. The same five holes of each upper and lower coupon of each stack were averaged to calculate the surface roughness for each stack under investigation, as displayed in Figure 14. For both the ALEMA and DMU, optimisation improved the surface roughness whereas the surface roughness for the Exechon increased marginally for optimised drilling parameters. Again, it is clear to see that all three platforms operated under 1μm of hole wall roughness.

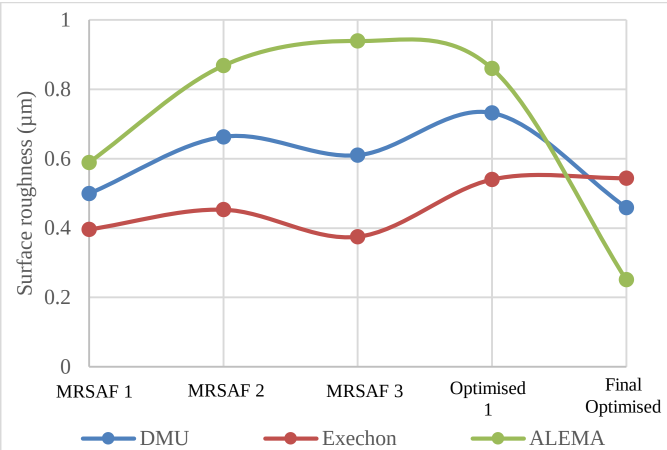

Figure 14. Average surface roughness of each stack under MRSAF and optimised parameters for each platform.

Although not directly measured, the countersink quality was taken into account during the 'engineering experience' phase of the optimisation process. Each platform produced adequate, chatter free countersinks when operating under MRSAF and final optimised parameters. That being said, each platform did encounter some chip extraction issues due to the ductile nature of the test material, as illustrated in Figure 15. Consequently, with respect to the vertical drilling orientation used in this investigation, the build-up of swarf reduced the effectiveness of chip extraction and hence it was possible for chips to be present on the surface of the test stacks. Resultantly, this produced normalisation issues for the pressure foot of the ALEMA platform.

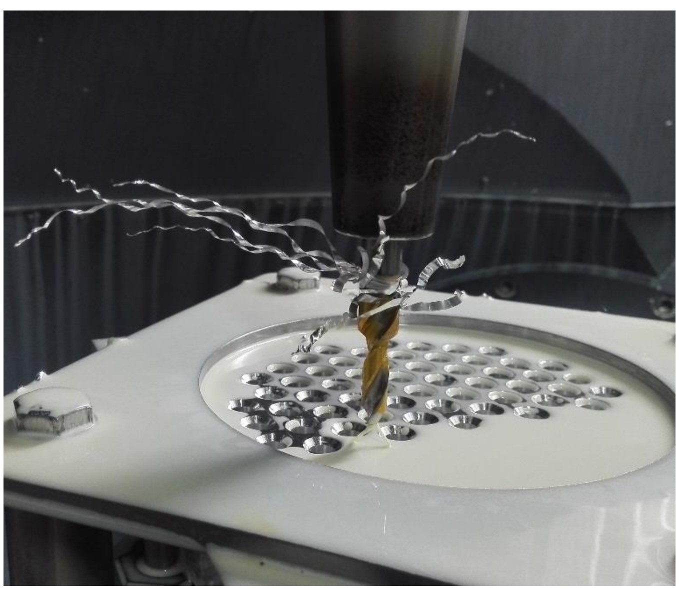

Figure 15. Swarf build up on DMU drilling platform

Tool Condition

The condition of the tool and the development of any wear was visually monitored at three locations along the primary cutting edge and at one location on the rake face, as illustrated in Figure 16.

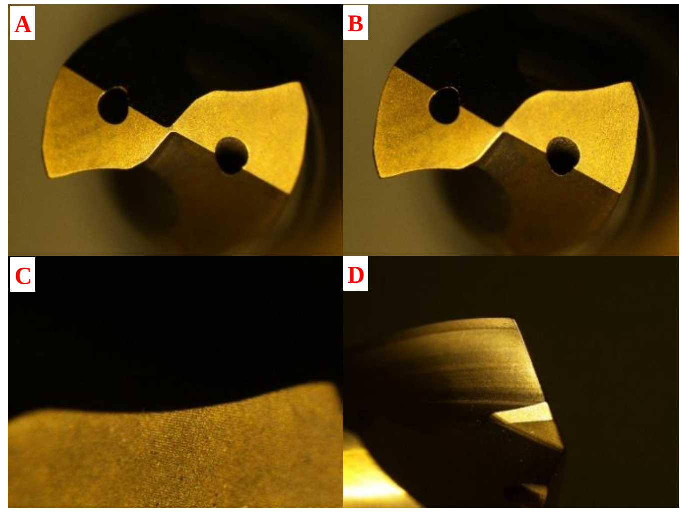

Figure 16. Microscopy locations for a fresh tool at: A) primary cutting edge near the chisel (15x), B) secondary cutting edge near the margin (15x), C) mid-point of secondary cutting edge (50x) and D) rake face (15x)

Comparison of tools which had completed the same linear cutting distance revealed, tool wear occurred at a similar rate across all platforms and the optimisation process did not affect the rate of tool wear for any platform. No visible edge chipping or tool fractures were recorded throughout the investigation. Any visible differences between cutting tool surface finish could be attributed to coolant application and heat build-up during the machining process. Figure 17 shows the progression of discolouration as the linear cutting distance increases for the DMU and Exechon platforms respectively.

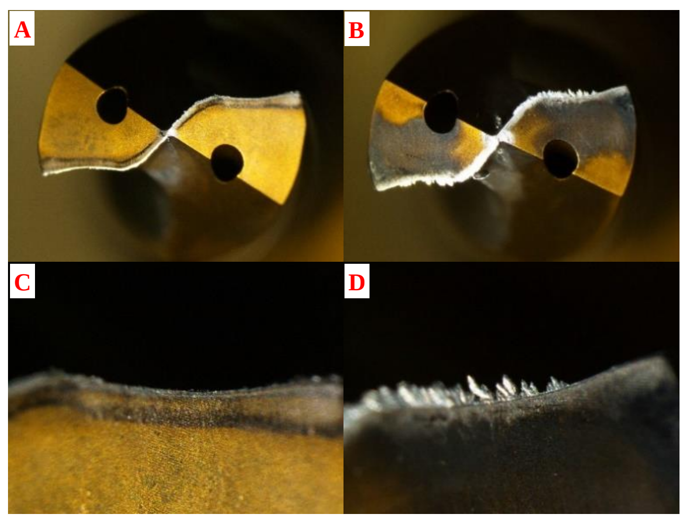

Figure 17. Cutting tool condition after 20 stacks (18m) under MRSAF for: A) DMU primary cutting edge near the chisel (15x), B) Exechon primary cutting edge near the chisel, C) DMU mid-point of secondary cutting edge (50x), D) Exechon mid-point of secondary cutting edge (50x)

Adhesion of test material to the tool known as built up edge (BUE), as displayed in Figure 18, was a prominent feature for all platforms, however this was expected when drilling aluminium alloy.

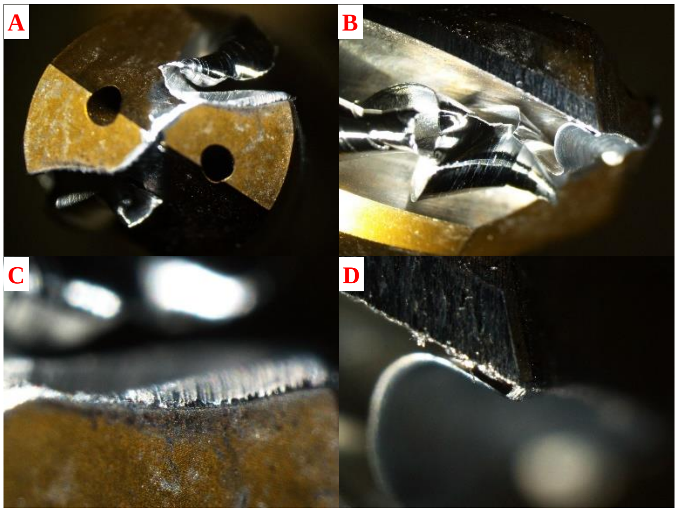

Figure 18. Development of BUE for the ALEMA at: A) secondary cutting edge near the margin (15x), B) rake face (15x), C) mid-point of secondary cutting edge (50x) and D) margin (50x)

Research Summary

This purpose of this research was to investigate the effects of static and dynamic platform characteristics on hole quality, tool condition and cycle time when drilling stacked aerospace materials. A precision CNC machine, hybrid parallel kinematic machine and robotic arm with drilling module were used to perform drilling trials through stacked aluminium alloy test coupons to determine the unique characteristics associated with each platform. A concise summary of the findings is shown below:

- The small, 5-axis CNC platform was found to be a stiff, static machine with a small, enclosed working envelope and superior coolant application abilities. Resultantly, this platform proved to be a highly capable machine which produced well finished, accurate holes in a very fast time with normal rate of tool wear.
- The HPKM platform was found to be marginally less stiff than the DMU (see Figure 6), yet mobile with a small, unenclosed working envelope. Coolant application resources were identified as less than desirable for the testing material. Subsequently, this platform demonstrated that it is of equal capability to the DMU, producing well finished accurate holes, in a fast time with normal rate of tool wear.
- The 6 D.O.F robot arm with drilling module was found to be significantly less stiff than the DMU (see Figure 6), but, like the HPKM, is mobile. The platform can operate within a large, unenclosed working envelope however, the coolant application in this case, was the least effective of the three platforms. Tool wear occurred at a normal rate.
- All three platforms benefited from the outlined optimisation process, resulting in the generation of platform specific drilling parameters and an increase in hole quality compared to MRSAF.

Conclusions

The conclusions drawn from this research have been done so in the knowledge that all platforms have solely been tested when vertically drilling 6.8mm holes through aluminium-aluminium aerospace stacks. Correspondingly, the conclusions from this research are as follows:

- Each platform was capable of generating aerospace quality holes, in terms of surface roughness, and hole diameter, regardless of the platform specific characteristics, such as stiffness or working envelope.
- Tool wear occurred at a similar rate across all three platforms, before and after optimisation. Any differences in tool appearance within this project could be attributed to the platforms ability to apply adequate coolant to the cutting zone. Exchanging the aluminium test material for a more difficult to machine material, such as carbon fibre reinforced polymers (CFRP), could potentially reveal differences in the rate of tool wear across the platforms.
- An effective optimisation methodology, compatible with all platform designs, was developed within this research and resultantly increased the capability of each platform, regardless of individual characteristics.

Future Research

A single testing material and small hole size was investigated in this research. Within current aerospace assembly practices, other more challenging drilling conditions exist. Therefore, investigations into alternate aerospace materials, hole diameters and non-traditional drilling methods, such as orbital drilling larger diameter holes through titanium-CFRP stacks, are stimulating avenues of future research.

Likewise, the findings of this paper and questions instigated therein, could be advanced by investigating the most cost effective way to drill aerospace holes in line with a modern day aerospace assembly case study, such as a wing box assembly. A deeper exploration of the commercial capabilities of various platforms through detailed consideration of platform characteristics, cycle time, cost, tool wear and hole quality under such a case study would be highly relevant to the aerospace assembly industry.

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Definitions/Abbreviations

NITC	Northern Ireland Technology Centre
CNC	computer numerically controlled
HPKM	hybrid parallel kinematic machine
AGV	automatic guided vehicle
MQL	minimum quantity lubrication
D.O.F	degrees of freedom
MRSAF	manufacturer’s recommended speeds and feeds
CMM	coordinate measurement machine
C.sink	countersink
Cpk	process capability index
Cp	process capability
BUE	built up edge
CFRP	carbon fibre reinforced polymers